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Groundwater Quality Monitoring of Western Coal Strip Mining: Preliminary Designs for Reclaimed Mine Sources of Pollution

General Electric Co.
Santa Barbara, CA

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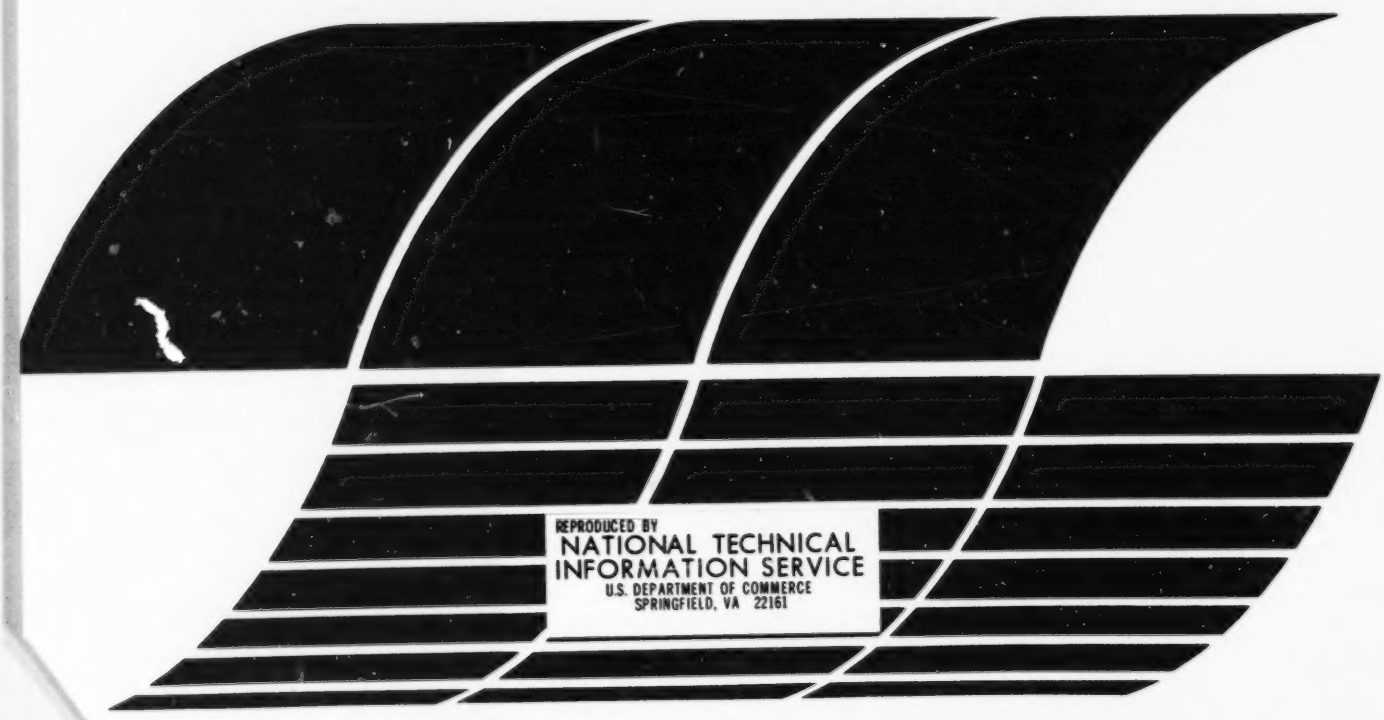

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16. ABSTRACT

This report is the fourth in a series of studies to assess the impact on groundwater quality of coal strip mining in the western United States. Presented are preliminary groundwater monitoring design guidelines for reclaimed mine areas, including regarded spoils and reclamation aids. The study area for this report is Campbell County, Wyoming, which overlies one of the major coal fields in the Powder River Basin.

The monitoring design consists of a sequence of data gathering, evaluation, and decision steps used to assess monitoring needs, provide alternative monitoring approaches to address these needs, and make preliminary recommendations. Cost estimates for required labor, operating expenses and capital outlay for each monitoring step are provided. Using the General Electric-TEMPO generic monitoring methodology (Todd et al., 1976), the following information assessment steps are evaluated for each pollutant source: identify potential pollutants, define groundwater usage, define hydrogeologic situation, study existing groundwater quality, evaluate infiltration potential, evaluate mobility of pollutants in vadose zone, and evaluate attenuation of pollutants in the saturated zone. Multiple passes through the assessment steps, with each pass comprising a more complete and costly data collection and evaluation process, are used to "scale-up" monitoring to a site-specific, cost-effective level.

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GROUNDWATER QUALITY MONITORING OF WESTERN COAL STRIP MINING:

Preliminary Designs for Reclaimed Mine Sources of Pollution

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FOREWORD

Protection of the environment requires effective regulatory actions based on sound technical and scientific data. The data must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of exposure to specific pollutants in the environment requires a total systems approach that transcends the media of air, water, and land. The Environmental Monitoring Systems Laboratory at Las Vegas contributes to the formation and enhancement of a sound monitoring-data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report presents the second phase of a study to design and verify groundwater quality monitoring programs for western coal strip mining. The development of a groundwater quality monitoring design for potential pollution sources and the pollutants associated with reclaimed mine sources of pollution is presented. The results herein will lead to a data verification effort. It is anticipated that the verification program will result in modification to this initial monitoring design.

Further information on this study and the subject of groundwater quality monitoring in general can be obtained by contacting the Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency, Las Vegas, Nevada.

Glenn E. Schweitzer
Director
Environmental Monitoring Systems Laboratory
Las Vegas

PREFACE

General Electric--TEMPO, Center for Advanced Studies, is conducting a 5-year program dealing with the design and verification of an exemplary groundwater quality monitoring program for western coal strip mining. The coal strip mining activity discussed in this report is located in Campbell County, Wyoming. In addition to active mine sources and reclaimed mine sources, the investigation covers secondary water resource impacts of municipal and industrial support programs which accompany the mining effort. The report follows a stepwise monitoring methodology developed by TEMPO.

This report represents the second phase of this research program. Described herein is the initial design of a groundwater quality monitoring program for potential pollution sources and pollutants associated with reclaimed mine areas.

In the next phases of this research program, the preliminary monitoring designs are to be verified with existing data. Initial verification study results may produce a reevaluation of the monitoring design presented in this report. The final product of the 5-year program will be a planning document for coal development companies and the various governmental agencies concerned with environmental planning and protection.

SUMMARY

Monitoring design guidelines to assess the impact on groundwater quality from reclaimed mine sources of pollution is the subject of this fourth report in a series developed for western coal strip mining.

The initial report (Everett, 1979) dealt with the identification of potential sources of groundwater quality impact; characteristics of potential pollutants; source-area hydrogeology and groundwater quality; and infiltration and mobility of pollutants in the subsurface. These assessments focused on a case study region around Gillette, Wyoming. Subsequent reports develop guidelines for groundwater quality monitoring programs for active mine and municipal sources of pollution.

Preliminary monitoring designs for reclaimed mine sources are presented in the following sections of this report. The term "design" is used in a broad sense here to mean a structured sequence of data-gathering, evaluation, and decision steps which result in a determination of what monitoring activities are needed and what the appropriate methods are for addressing these needs. The recommended monitoring approach for each potential pollution source constitutes the recommended design.

Potential sources of groundwater quality impact associated with reclaimed mines have been grouped into two categories for consideration in this report:

- Spoils, including overburden, interseam partings, coal, coal refuse, and coaly waste
- Reclamation aids, including fertilizers and soil amendments.

Ranking of pollution sources is based on a sequence of data compilation and evaluation steps which comprise a conceptual design methodology. This methodology is discussed by Everett (1979). The three basic criteria used to develop the source-pollutant ranking are:

- Mass of waste, persistence, toxicity, and concentration
- Potential mobility
- Known or anticipated harm to water use.

An extensive study of the hydrogeology of mine areas, coal strip mine development, and environmental effects has shown that significant information

voids exist with regard to mobility and potential pollutant characterization of source materials within the hydrosphere. Therefore, professional judgment plays a large role in proposing this preliminary source-pollutant ranking which is as follows (Everett, 1979):

Coal Strip Mining:
1. Spoils (below water table)
2. Spoils (above water table below ponds or streams)
3. Pit discharge (to streams).

Of these ranked pollution sources, spoils are described in this report and pit discharge to streams via sedimentation ponds is discussed in the preliminary design report for active mine sources.

The generic monitoring methodology which was utilized herein was developed by General Electric--TEMPO and includes the following information assessment steps:

- Identify potential pollutants
- Define groundwater usage
- Define hydrogeolgic situation
- Study existing groundwater quality
- Evaluate infiltration potential
- Evaluate mobility of pollutants in the vadose zone
- Evaluate attenuation of pollutants in the saturated zone.

Monitoring needs and alternate approaches to address these needs are evaluated at each step. Technical assessment and monitoring costs relative to the potential for impact on groundwater quality result in selection of a monitoring approach. Quite often, information gathered through the selected monitoring approach for one step will refocus monitoring needs and provide a data base for alternate steps. It is important to note that each step in this design sequence is a decision point. If the technical assessment indicates the absence of potential for impact to groundwater quality, then this conclusion is the end product for the monitoring design.

Multiple passes through the methodology steps, with successive passes dealing with more detailed data sets and generally higher costs for developing required information, are employed to "scale-up" to an appropriate and cost-effective level of monitoring effort. Thus, at specific sites, different monitoring designs may result for any of the potential pollution sources considered in this report.

The above-outlined sequence of steps is followed through entirely and a monitoring approach is "selected." As with the designs developed in previous

reports, these guidelines are generally applicable throughout the western coal-development States. Case studies have been included in earlier reports to balance this factor; however, none of the mines within the study area are engaged in the reclamation activities, and data for case studies are lacking. For this reason, no site-specific samples have been included herein.

Tables A-1 and A-2, Appendix A, give summaries of preliminary monitoring design for regraded spoils and reclamation aids, respectively. For each monitoring step, needs and alternative monitoring approaches to meet these needs are discussed. Preliminary monitoring recommendations and cost allocations are selected from these alternatives. Major cost items (i.e., develop a monitor well) are initiated in response to evaluation of specific pollution sources which are judged to constitute a signficant threat to the groundwater quality. This point is not brought out in Tables A-1 and A-2 and should be kept in mind when evaluating the cost-effectiveness of the monitoring designs provided herein. Costs are provided for the preliminary recommended monitoring approach which has been selected from a series of alternative monitoring approaches.

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LIST OF ABBREVIATIONS

afa	acre-feet annually
CEC	cation exchange capacity
DO	dissolved oxygen
EC	electrical conductivity
Eh	oxidation reduction
fc	infiltration rate
ppm	parts per million
PVC	polyvinyl chloride
SAR	sodium absorption ratio
TDS	total dissolved solids
TOC	total organic carbon

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SECTION 1

MONITORING DESIGN FOR SPOILS

INTRODUCTION

The Surface Mining Control and Reclamation Act of 1977 has resulted in a number of reclamation and enforcement provisions for strip mines (U.S. Department of Interior, 1977). Section 715.17 of the Surface Mining Reclamation and Enforcement Provisions deals with protection of the hydrologic system. The provisions state that changes in water quality shall be minimized such that the postmining use of the disturbed land is not adversely affected. Furthermore, operations shall be conducted so as to minimize water pollution. Practices to control and minimize pollution include sealing acid-forming and toxic-forming materials and selectively placing waste materials in backfill areas. Lastly, when operations are conducted in such a manner that may affect the groundwater, water levels and groundwater quality shall periodically be monitored using wells that adequately reflect changes resulting from such operations.

The Priority Ranking Report (Everett, 1979), carried out during the first year of this study, gave spoils the highest priority for monitoring among the sources of potential pollution directly related to coal strip mining. Spoils deposited below the water table received a higher priority than spoils above the water table. Spoils above the water table are of concern if they are located under a source of leaching fluid, e.g., a pond, stream, or irrigated area.

IDENTIFY POTENTIAL POLLUTANTS

Sodium and alkaline spoil materials have the greatest potential for contributing pollutants to groundwater. Overburden materials with high salt concentrations left on the final graded spoils cause immediate revegetation problems. In addition, saline spoils dressed with topsoil can cause problems through saline seeps and by the upward migration of salts into the topsoil. Unrecovered coal, parting material, refuse, and other waste materials buried in the spoil can be major sources of pollutants.

Primary pollutants may include soluble salts, with sulfates of calcium, magnesium, and sodium predominating. Most spoils also contain appreciable quantities of calcium carbonate. Normally, very few readily soluble chlorides, carbonates, or bicarbonates are present. Also, plant-available forms of phosphorus are normally low in the spoils and overburden. Shales commonly contain appreciable exchangeable ammonium-nitrogen when weathered. Nitrifying

organisms are scarce at depths of about 8 to 10 meters because of lower soil temperatures. Consequently, nitrate forms of nitrogen predominate in the upper levels and ammonium-nitrogen predominates at the lower levels.

The spoils in the Gillette area are generally neutral to alkaline. Therefore, heavy metal contaminants may not be a major problem. However, coal wastes buried within the spoil can become sources of trace element pollution depending upon the minerals contained in the coal.

Monitoring Needs

Knowledge is needed of the general chemical characteristics of the regraded spoil. Specifically, information is needed on the type, concentration, and distribution of elements and/or compounds that become sources of groundwater pollution, particularly for those areas of regraded spoil in contact with free underground water and/or whose leachate possibly could contribute potential pollutants to the groundwater system.

Alternative Monitoring Approaches

It would be desirable to have records maintained of the location and amount of spoils that are emplaced during the monitoring program. Also, the distribution of materials that have a significant pollution potential, such as the shale layers above the coal, could be monitored.

Maps could be compiled on a monthly basis indicating both the location and elevations of spoils material in the reclaimed area. Gross volumes or weights of material could be estimated. Records could be kept for all materials which receive special handling in the spoils, such as coaly wastes and shale partings. Amounts and locations of these materials in the spoil could be specified. A photographic record of the face of the spoils in the pit could be maintained. Such a record could substantiate, for example, that more consolidated formations are being selectively placed in the bottom of the spoils.

The composition of materials which make up regraded spoils could be determined. Random composite samples could be taken at points on a grid covering the entire spoil area. The spacing of the points on a second sampling pass could be determined by the variability and toxicity of material encountered during presampling.

Alternatively, a priority sampling scheme could be employed. The objective would not be to characterize the entire area of spoil by one or more chemical elements or compounds, but rather to delineate selected areas that contain pollutants which, due to their location or toxicity in the regraded materials, would have increased potential of newly introducing or raising existing concentrations of pollutants in the groundwater system.

These areas could first be delineated on the basis of their relation to existing or predicted water table elevations within the spoil materials. The strata thus delineated could be sampled in two stages. Initially, samples

could be taken at grid points of about 300 feet* apart. Samples could be taken at each point throughout the entire depth of spoil at no less than 5-foot intervals. Sampling could be made at closer intervals if particularly toxic materials are encountered. Hand-driven samplers can be used to depths of about 10 feet with power equipment required for deeper sampling. The subject of spoils sampling in areas of potentially toxic material placement has not been addressed by State regulations.

The frequency for sampling solids in the spoils is presently difficult to determine. In part, this depends on the variability of materials encountered at any time in the pit, including overburden, partings, and coaly wastes. Part of this variation will be known at the time of mining due to the quality of coal desired and for purposes of reclamation. The frequency of sampling could be related to this variability. During the first year, monthly grab samples could be collected. After the first year, the frequency could be adjusted based on past experience and the dynamic chemical characteristics of the regraded spoils.

Spoil samples could be analyzed for pH, electrical conductivity, total soluble salts, soluble cations, base saturation, sulfate, nitrate, total nitrogen, and total organic carbon. Tests could be run on the saturation extract for powdered samples. In addition, boron and fluoride levels could be determined. The content and character of pyrite or other forms of iron sulfide largely control the potential acidity of water contacting spoils and should be evaluated. The soluble calcium content of the spoils also exerts a controlling influence on the pH.

Drever, Murphy, and Surdam (1977) discussed trace elements associated with the Wyodak coal seam at the Black Thunder mine. For purposes of groundwater quality monitoring, vanadium, manganese, nickel, copper, zinc, arsenic, selenium, lead, barium, cadmium, chromium, iron, molybdenum, and silver could receive priority due to their importance for water use and/or their probable relative mobility in soil aquifer systems.

The organic chemical content of certain materials in the spoils could be substantial. This is particularly true for coaly wastes and shales. A gross indication of the composition could be obtained by determining the total carbon and total nitrogen content. If specific organic chemical constituents are found in groundwater in the spoils, then solid materials in the spoils could be sampled for such specific constituents at a later time.

The radiological content of the spoils could be periodically evaluated in a gross manner by determining the uranium and thorium contents. Samples could also be analyzed for alpha activity, beta activity, and radium-226 activity.

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* See Appendix B for conversion to metric units. English units are generally used in this report because of their current usage and familiarity in industry and the hydrology-related sciences. Certain units, expressed in commonly used metric units (e.g., concentrations), are expressed in milligrams per liter or similar units.

Preliminary Recommendations

All existing information concerning the location and nature of backfilled spoil material should be obtained and arrangements should be made with the mining company to receive ongoing information of this type. If such data are not being gathered, backfilled areas would be mapped and photographed, including items such as spoil location, elevation, and composition. These maps would be updated frequently, possibly on a monthly basis.

The composition of spoil materials would be determined using a priority sampling scheme, as discussed above. Sampling frequency would depend on the variability of spoil material and the rate at which an area is backfilled. Samples would be analyzed for the constituents discussed above.

Costs for this step would include: labor costs for gathering existing information, mapping spoils, and collecting samples; operational costs for mapping, sampling, and spoil analyses; and capital costs for sampling and photographic supplies, and equipment. These costs are given in Table A-1.

DEFINE GROUNDWATER USAGE

The largest quantity of groundwater used by the coal strip mines comes from pit discharge. Dust suppression is the primary use of this water. Wells supply water for drinking, bathing, and cleanup. Irrigation of regraded spoils is not planned at present, but may be a possibility in the future.

Monitoring Needs

The primary monitoring need will be to determine whether backfilled areas are to be irrigated and, if so, what the irrigation requirements will be in terms of water quality and quantity.

Alternative Monitoring Approaches

The present and anticipated future use of groundwater for reclamation could be assessed through discussions with mine personnel. If the spoils are to be irrigated, simple irrigation metering devices could be installed in the supply lines. The volume of water needed for irrigation could be estimated by assuming a consumptive use of 1 to 4 acre-feet of water per acre being revegetated.

Preliminary Recommendations

The recommended preliminary approach is to determine whether spoils are to be irrigated. No further monitoring would be planned until irrigation is decided upon. The only cost for this approach would be labor for discussions with mine personnel.

DEFINE HYDROGEOLOGIC SITUATION

Most of the mines in the Powder River Basin have groundwater conditions between those of the Wyodak mine, where the pit (located below the water table) will most probably become a lake, and the Kerr-McGee mine (reportedly located above the water table) where the spoils will not become saturated. The increase in volume when the overburden is spoiled is about 30 percent. Where the spoils become saturated, the possibility arises that the spoils could become manmade aquifers. Where the overburden is predominantly sandstone or alluvium, the permeability of these aquifers will be high. Permeabilities will be low where the overburden is shale and/or siltstone. In addition, dragline-dumped spoils will have a greater permeability than scraper-dumped spoils.

Monitoring Needs

There are two primary needs for spoil areas which may be reinvaded by groundwater after mining: definition of the existing groundwater system (i.e., depth of water table, piezometric surface, thickness of aquifer, direction and rate of flow within the aquifer, and the permeability of aquifer materials), and development of methods for predicting the rate of invasion of groundwater into the recontoured spoil and the final height of the water table.

Alternative Monitoring Approaches

Existing data could be gathered for any wells in the mine area. These data may include: water-level measurements, pump test results, and lithologic or geophysical logs. Geologic data may also be available from test holes or oil wells in the area.

Water-level monitoring could be initiated in existing wells to determine the depth of water, recharge and discharge areas, and direction of flow. Aquifer tests could be conducted in existing wells for determination of the transmissivity and storage coefficient and possible vertical leakage.

If necessary, additional wells could be drilled to supplement existing wells in the area. These could be pump-tested and included in the water-level monitoring program. These holes could be geophysically logged for geologic information and permeability tests could be conducted on samples from both overburden and spoil material.

Models could be constructed or modified to help predict the behavior of groundwater systems after the area is mined and reclaimed.

Preliminary Recommendations

Preliminary steps in defining the hydrogelogic situation would be to evaluate all existing information. If necessary, pump-testing and water-level monitoring would then be initiated. The need for additional wells and data collection would then be determined.

Costs for work with existing facilities would include: labor costs for gathering and interpreting existing data, monitoring water levels, and conducting pump tests; operational costs for supplies; and capital costs for well sounders. These costs are given in Table A-1.

STUDY EXISTING GROUNDWATER QUALITY

Shallow groundwater quality can vary widely in Campbell County. Groundwaters in the Wasatch Formation are usually of the calcium sulfate type and have a range in TDS of 500 to 6000 ppm. pH values range from 7.7 to 8.1. Trace element studies indicate that problems may exist with the following elements: arsenic, cadmium, lead, selenium, and possibly uranium (Everett, 1979).

Coal seam waters have been found to change in quality from calcium sulfate to sodium bicarbonate as the water migrates downdip. Coal seam TDS values range from 500 to 3500 ppm, and values for pH range from 6.9 to 8.2. Trace elements of concern include, but are not limited to: arsenic, cadmium, copper, lead, and selenium (Everett, 1979).

Monitoring Needs

An essential monitoring need is the establishment of baseline data concerning the chemical quality of groundwater both in the vicinity of backfilled spoils and on a regional basis.

Alternative Monitoring Approaches

Available water quality data could be obtained and examined. A water sampling program could be initiated to characterize the current groundwater quality in the vicinity of backfilled areas. Samples could be collected from existing wells, wells constructed during the previous step for characterization of the hydrogeologic situation, and additional wells drilled, as necessary, in the spoil material itself. Alternative methods for sample collection and analysis are described in the monitoring design for stockpiles in the active mine sources report.

Preliminary Recommendations

The recommended approach is to obtain and evaluate existing water quality data. A water sampling program would then be initiated, if necessary, using existing wells and any installed during the previous step. The first five samples from each well would be analyzed extensively (including calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate, phosphate, silica, ammonia, nitrogen, nitrate-nitrogen, total nitrogen, iron, manganese, zinc, copper, chromium, cadmium, arsenic, molybdenum, selenium, and uranium). Parameters found to be in excess of recommended limits would be delineated. Periodic field checks would then be conducted for such parameters as pH, electrical conductivity, dissolved oxygen, nitrate, and chloride, with samples being collected for laboratory analysis when marked changes occur between field checks. Samples would be analyzed for major constituents and

those trace constituents previously found to be in excess of recommended limits.

Costs for this step would include: labor costs for examining existing data and collecting samples, operational costs for sample analyses and supplies, and capital costs for pumps or bailers, a field kit for determining pH, chloride, and nitrate, and conductivity and dissolved oxygen meters.

EVALUATE INFILTRATION POTENTIAL

Infiltration is the combined process of the entrance of water at the soil surface and its subsequent downward movement through the soil media. It is affected both by the condition of the surface and the nature of the soil material. A large portion of the spoil material at the Campbell County mine sites is derived from shale and siltstone. Therefore, it is fine textured (excluding large rock fragments) with a high clay fraction, often above 20 percent. Furthermore, the characteristic rapid decomposition of shale when exposed to weathering releases salts which tend to inhibit flocculation and the formation of soil structure. If the materials have an unchangeable sodium percentage greater than 15 (sodic), as they often do, they may form a surface essentially impermeable to water.

Infiltration rates on spoil materials may vary from as high as 20 inches per hour (alluvial material) to 0.2 inch per hour (shale material). An average infiltration of about 0.5 inch per hour is common on spoil with high shale and clay components.

Regrading and surface treatment for reclamation (pits, furrows, berms, etc.) create depressions for surface water retention and provide extended periods of a steady supply of water at the soil surface that might sustain infiltration for long periods. However, retention basins often become impermeable from the sealing effects of fine material washed in by surface runoff. Their effective life is only a few years, under the best conditions. In areas where underground fires occur, infiltration may be greatly influenced due to cavitation and subsequent cracking and caving at the surface which can allow the entry of free water. If the mining operation is efficient, these conditions appear in small areas, are short-lived, and occur infrequently.

An important source of possible groundwater pollution from infiltrating waters can occur beneath stream beds after they are mined and if stream channels are reconstructed across the spoil material. Creeks which are losing streams in their natural state will probably also become reestablished as such and will have a high potential for contributing significant amounts of surface water to the groundwater system.

Monitoring Needs

Infiltration capacity is an important parameter in characterizing the hydrologic behavior of spoil. Information on infiltration is needed to supplement other data (e.g., precipitation, snowmelt, evaporation potential) necessary to classify the potential of spoil materials to contribute pollutants to the groundwater system.

Alternative Monitoring Approaches

Infiltration capacity could be determined by (1) laboratory tests of spoil permeability, (2) ring infiltrometers, or (3) sprinkler-type infiltrometers. Laboratory permeability tests are of doubtful value because of the disturbed nature of the samples, their small size, and the associated difficulty of obtaining representative samples. Field infiltrometer tests can be useful in comparing differences of magnitude between sites and are useful for irrigation purposes where the supply of water at the soil surface is steady, but they cannot be relied upon to give quantitative representation of actual infiltration under natural rainfall or snowmelt.

The sprinkler-type infiltrometers are generally preferred over the ring type. They more closely approximate natural rainfall (i.e., raindrops and zero head), provide a measure of surface runoff potential, and, with some devices, give estimates of erosion potential. They are also difficult to operate, require considerable auxiliary equipment, and are expensive. The ring devices are very simple and provide a quick means of obtaining relative values of infiltration capacity for different sites.

Measurement sites could be chosen randomly or selected on the basis of previous information. Ideally, sampling should be completely random or systematic with random starts; however, this would require an inordinate amount of effort to characterize a large area. Interpretation would be complex because of the point-to-point variability. Stratification could help reduce variability if an average were sought for the entire area.

Sites could be selected for infiltration studies on the basis of chemical and physical characteristics and the depth of spoil overlying the water table, determined in Step 1 (Identify Potential Pollutants). For example, an area of saline spoils might be given a higher priority than one of sodic spoils (other factors being equal) because of a higher infiltration capacity. Infiltration runs could be made at points within such areas which are judged to be most representative of the general condition.

Sufficient samples could be taken to achieve a reasonable degree of precision; 10 percent of the mean final infiltration rate (fc) at the 95 percent confidence level is desirable. For most spoil materials, the final rate is obtained within 2 hours.

Infiltrometer data could be used with precipitation measurements and historic records of precipitation to estimate the maximum probable infiltration under the prevailing climatic conditions at the mine site.

Preliminary Recommendations

Infiltration capacity would be determined using a simple ring infiltrometer because of the economics and ease of obtaining data quickly from a large number of sites. Sites would be selected on the basis of information gathered in Step 1. Precipitation data would be obtained from existing records for the area.

Costs for this step include: labor costs for infiltration measurements and data collection, and capital costs for ring infiltrometers. These costs are given in Table A-1.

EVALUATE MOBILITY OF POLLUTANTS IN THE VADOSE ZONE

The mobility of water and the pollutants it might carry depends upon the infiltration characteristics of the surface and the distribution size, and composition of materials comprising the spoil. Spoils, despite the mixing that occurs during overburden removal and subsequent regrading, are very non-homogeneous. Vertical and areal variations are greater, in most cases, than those of natural soil or geologic bodies. It is to be expected, particularly if opportunities exist for free water to enter the surface, that temporarily perched free water may develop in the soil where impermeable layers are formed during the spoiling operation.

Most of the spoil material is composed of rocks with interspaces filled with fine material. In removing and regrading the overburden, the spoil increases in volume; swell factors of 20 to 30 percent are common. Permeability for air and water is increased, but this is usually offset by the high colloidal content of the spoil material. Sodic tendencies are common in spoils; thus, subsurface piping may occur which would allow free water flow within the spoil. Similarly, the burning of combustibles in the spoil also creates opportunities for free water movement by creating voids and cracks. Water movement in the vadose zone will occur as unsaturated, unsteady flow in most of the spoil areas. However, where mining occurs in stream valleys, and where the stream bed is redeveloped on the mine spoil, the development of saturated flow is very likely because of the constant availability of water at the surface and the high permeability of the alluvial spoil material.

Monitoring Needs

There is a need to monitor the quantity and quality of water moving through the vadose zone of spoil to groundwater. Particular attention needs to be given to the more critical sites; i.e., those sites with one or more of the following characteristics: high infiltration capacities and/or high permeability at the surface, shallow depth of spoil above the water table, and concentrations of potential pollutants within the spoil.

Alternative Monitoring Approaches

A survey could be conducted and maps developed of the regraded spoil to delineate areas by their potential for contributing water and/or pollutants to groundwater. The survey would require information on: hydrologic characteristics (high, medium, and low infiltration characteristics), topographic position (swales, depressions, etc.), predominant types of material (alluvium, shale, siltstone, sandstone, etc.), conditions of the material (sodic, alkaline, normal, etc.), depth to existing or predicted future water tables, and anomalies (excessive amounts of partings, unrecovered coal, and/or wastes, and the presence of underground combustion).

Thus, in addition to topography and spoil-type mapping, the maps would include: delineations of free water surfaces (presently existing on future possibilities), the results of soil sampling and analyses, infiltration characteristics, and the existence and depth of water table.

Using overlays or computer graphics, the critical areas of spoil could be delineated and prioritized on the basis of their potential for contributing to groundwater problems. For example, an area with spoil material that has a high infiltration capacity, which lies above a shallow water table in an area where free water concentrates on the surface, and whose spoil material contains potential pollutants, would be given the highest priority and would warrant the most intensive monitoring.

Since the greatest opportunity for the movement of water and the potential pollutants it might carry to the groundwater system will occur as unsaturated, unsteady flow, it will be necessary both to sample changes in water content and measure the pressure changes with time and depth.

The three most common means of measuring moisture changes are: gravimetric, electrical resistance, and neutron scattering. Changes in pressure (negative head) can be measured with pressure plates, tensiometers, or psychrometers.

For measuring moisture content, electrical resistance methods are difficult, if not impossible, to quantify with confidence. Gravimetric methods give good results but eventually destroy the sampling site and are time consuming and labor intensive. Neutron probes and loggers also present technical and logistical problems, but are a satisfactory compromise. Negative pressures in soils can be measured with pressure plates, but they are difficult to install and interfere with flow. Tensiometers, although simple, require diligent maintenance and will not give reliable results below moisture contents corresponding to about 3/4 of a bar pressure. At lower moisture contents, soil psychrometers could be used instead of, or to augment, the tensiometers. These devices require skill and experience to interpret accurately. They are ineffective in wet soils, but can give good results at lower moisture contents.

It is also possible, in theory, to simulate moisture flux in soil media using field and laboratory determined values of the necessary parameters. However, models have been developed to date only for homogeneous and simple layered systems and have little application to mine spoils because of the inhomogeneities that exist in most spoils and the difficulty of obtaining the parameters required by the models.

Preliminary Recommendations

Based on the considerations above, neutron probe access wells are recommended on critical sites extending through the spoil well into the existing or predicted future saturated zones. Tensiometers would be installed at three depths above the capillary fringe region of the water table at integrals no more than 2 feet apart adjacent to the access wells. Since moisture flow

will be negligible at pressures less than 1 bar, psychrometers will not be necessary.

The sampling should be conducted in two stages. Initially, all sites delineated in the survey should be instrumented with an access tube extending through the entire depth of spoil. Monitoring throughout the first year on a monthly basis will allow the most obvious nonproblem sites to be eliminated from subsequent monitoring. Questionable sites should be monitored for as long a period as necessary to show that they may present problems or that they may also be eliminated. It is expected that the final number of problem areas will not be large. Significant flow of water from the low precipitation in the area will only occur in the most permeable and/or shallow materials. Nevertheless, monitoring should be intensified on those sites which exhibit a high potential for contributing to the groundwater system.

It is recommended that additional access tubes be installed on the critical sites in a second stage. It is assumed that where problems exist, moisture contents will be high. Therefore, tensiometers would be installed adjacent to the access tubes to measure pressure differences for the determination of flow volumes.

The number of installations to be made would depend upon cost, the variability encountered, and the desired precision. Standard sampling analyses which incorporate these variables would be used to establish the sampling intensity.

Costs for this step include: labor costs for installation of access wells and tensiometers and for sampling, operational costs for installation, and capital costs for wells, tensiometers, and a neutron logger. These costs are given in Table A-1.

EVALUATE ATTENUATION OF POLLUTANTS IN THE SATURATED ZONE

There are two types of saturated zone monitoring. One type could be done while pit dewatering is still in progress adjacent to a specific area of spoils. In this case, pit water, water from wells tapping nearby coal and overburden, and monitor wells in the spoils could be sampled. The second type is for spoils beyond the influence of pit dewatering. In this case, monitoring of pit discharge is unnecessary. However, monitoring would still be necessary for groundwater in materials adjacent to the spoils.

Monitoring Needs

Monitoring needs for the saturated zone include: aquifer tests on saturated spoils, determination of the extent of saturated spoils, determination of groundwater flow direction in the spoils, and determination of the quality of groundwater in the spoils, including trace elements, organic chemical constituents, and radiological constituents. Wells in the Wasatch Formation, coal seam, and underlying Fort Union Formation are needed in close proximity to the spoils. Groundwater conditions in undisturbed materials adjacent to the spoils must be understood in order to interpret the results of monitoring groundwater in the spoils.

Alternative Monitoring Approaches

The aquifer characteristics for, and water levels in, the emplaced spoils need to be determined. Also, the site-specific hydrgeologic framework for undisturbed materials adjacent to the spoils must be developed, including subsurface geology, water levels, aquifer characteristics, and groundwater quality. Most of this information could be gathered in the course of gathering groundwater quality data through monitor well construction.

A number of new wells could be drilled in the spoils after emplacement. These would be constructed while pit dewatering is still occurring nearby. These wells would be 14-inch-diameter holes equipped with 8-inch-diameter casing to allow proper pump testing. PVC pipe would be used for casing and the new well would be packed with gravel of known composition. The casing would be perforated opposite the zone expected to eventually be saturated when pit dewatering ceases in nearby areas. An annular seal would be placed opposite the upper 10 to 20 feet of the well. The wells would be properly developed upon completion to remove drilling mud or other foreign material. The top of the casing would extend several feet above the ground surface and a locking cap installed. Barriers would be installed to prevent destruction.

Wells in the spoils could be pump tested to determine aquifer characteristics once water levels have recovered from nearby pit dewatering. It would be advisable to conduct a test with the maximum possible saturated thickness.

In order to interpret the results of monitoring groundwater in saturated spoils, additional monitoring is necessary for groundwater in materials adjacent to the spoils. This includes Wasatch Formation overburden, coal, scoria, alluvium, and Fort Union Formation underburden, depending on the particular area. Existing monitor wells could provide some indication of regional groundwater conditions in the coal seam and overburden. However, regional groundwater conditions are poorly known for alluvium and the Fort Union Formation beneath the coal. In the early stages of mining, when pit discharge is occurring near emplaced spoils, pit discharge itself could be monitored, as well as additional wells in native materials adjacent to the spoils, particularly in an upgradient direction. This would require a minimum of several monitoring wells in the coal, several additional monitor wells in the overburden, and possible additional wells in the alluvium and underburden.

Both solid and liquid samples could be collected from the saturated zone. Some solid material could also be sampled during emplacement. To allow interpretation of the results of groundwater quality monitoring, solids penetrated by the monitor well could be sampled. Since some of the materials in the spoils are well consolidated, the optimal method of drilling is uncertain. However, drill cuttings could be collected in any case. Sampling of solids may provide invaluable data to evaluate factors such as trace metal migration in groundwater. Additional holes could be drilled into spoils periodically near the monitor wells to allow sampling and analysis of solids to correlate with the results of groundwater quality sampling.

Once the optimal pumping duration has been determined for water sample collection from wells, samples could be collected monthly for the first year.

The results of the first year could be used to determine the proper sampling frequency for the duration of the monitoring program. Climatic factors, such as liquid and solid precipitation events, should be considered in determining the exact date of collection of each sample. The pump tests in spoils would allow ample opportunity to collect samples for chemical analyses over several days or weeks. For pit discharge, results may be available from existing monitoring programs for that source. Pit discharge is monitored at the point of discharge to surface water for a few parameters. Grab samples could be collected on a weekly basis for 1 year and the frequency adjusted thereafter. However, the results of pit discharge sampling would be difficult to interpret with regard to specific pollutant sources, such as the spoils, unless a complete monitoring program for the sources of pit discharge was also in effect.

Solids beneath the water table could be analyzed for similar determinations specified for spoils as discussed earlier under the step, Identify Potential Pollutants.

For water, the major inorganic chemical constituents could be determined, in addition to pH, total dissolved solids (residue (180°C), and electrical conductivity. Such determinations allow comparison of cation-anion sums, total dissolved solids versus electrical conductivity, and calculated total dissolved solids versus residue. Occasional samples could have total dissolved solids (ignition 365°C) determined. Boron, fluoride, and various nitrogen forms could also be determined on occasion. An exhaustive suite of trace elements could be determined on at least one sample of water taken from each well near the end of the pump test. This would aid in selecting determinations to be made on a routine basis. Iron, manganese, arsenic, selenium, cadmium, chromium, lead, molybdenum, and vanadium could be determined frequently. Also, the results of the pollutant-source sampling program could be used to choose the trace elements of importance in groundwater quality monitoring.

The gross inorganic chemical composition of groundwater could be determined through analysis of dissolved carbon. More detailed determinations could be recommended after results have been obtained from the gross determinations. Uranium and thorium content and gross alpha activity, gross beta activity, and radium-226 activity could be determined on several water samples from each well and the pit discharge early in the program to provide an indication of the radiological composition of groundwater in the spoils.

A similar procedure could be used for analyses of water samples collected from monitor wells in undisturbed materials near the spoils.

Preliminary Recomendations

It is estimated that each year from 50 to 100 acres of spoils at each mine will be reclaimed. Annually, about six monitor wells should be constructed in the spoils. These wells would be an average of 100 feet deep and equipped wth 8-inch-diameter PVC casing. Wells installed during the first year would be pump tested for 1 week. This would require 7 days each for three individuals per well. Approximately three water samples would be analyzed from each pump test. An average of three samples of solid materials

penetrated by the monitor wells would be analyzed for each well. Samples of pit water could be obtained from the sump pump at the bottom of the pit.

A monthly sampling frequency based upon average groundwater flow and discharge rates is initially recommended for water from monitor wells and pit discharge. If the flow rates and the sample parameter values vary widely, increased sampling may be required. A portable submersible pump, generator, tripod, winch, pump column, discharge line, and electric cable would be necessary. It is estimated that three wells could be sampled in 1 day and two individuals would be required. Sampling of the pit discharge would involve no extra time.

Spoils below the water table can be analyzed for the same constituents specified for solids under Identify Potential Pollutants.

For water samples, the following should be determined routinely:

Calcium	Boron	Magnesium	Fluoride
Sodium	Total nitrogen	Potassium	Silica
Carbonate	Iron	Bicarbonate	Manganese
Sulfate	Arsenic	Chloride	Selenium
Nitrate	Lead	pH	Cadmium
Total dissolved solids (residue at 180°C)	Chromium	Electrical conductivity	Dissolved organic carbon

Several samples collected early in the program, such as during pump tests, should be analyzed for:

Total dissolved solids (ignition at 365°C)	Antimony	Iodide	Titanium
	Bromide	Rubidium	Vanadium
Strontium	Nickel	Aluminum	Copper
Cobalt	Zinc	Cesium	Barium
Uranium	Molybdenum	Thorium	Silver
Alpha activity	Tungsten	Beta activity	Radium-226 activity

Costs for this step would include: labor costs for drilling supervision, sampling, and interpretation of results; operational costs for drilling, miscellaneous sampling equipment, and analyses of water and solid samples; and capital costs for wells, pumps, etc. These costs are given in Table A-1.

SECTION 2

MONITORING DESIGN FOR RECLAMATION AIDS

INTRODUCTION

According to Tisdale and Nelson (1975), 20 elements have been found to be essential to the growth of plants. Not all are required by all plants, but all are necessary to some plants. The elements required by most plants are carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, boron, iron, manganese, copper, zinc, molybdenum, chlorine, cobalt, vanadium, sodium, silicon, and potassium.

The first three, with nitrogen, phosphorus and sulfur, constitute a plant's living matter or protoplasm. Elements other than carbon, hydrogen, and oxygen are termed mineral nutrients and are obtained by plants from the soil. The elements nitrogen, phosphorus, and potassium have been classed as major nutrients; calcium, magnesium, and sulfur as secondary elements; and the remaining mineral nutrients as microelements.

It should be noted that these classifications are arbitrary and are probably based on the quantities of mineral elements required in the majority of fertilizer programs. As a very general rule, the major elements are needed in the largest amounts and the microelements in the smallest.

Selection of the kinds and amounts of soil fertility treatments depend upon: the crop and its nutrient requirements, the ability of a given soil to supply those nutrients, the climatic factors that affect crop growth and fertility response, management and cultural practices, and the presence or absence of damaging chemicals or pathogens. In the evaluation of the pollution potential of fertilizers applied to reclaimed coal strip mine lands, all of the aforementioned factors, excepting the last item, will be essential considerations in the assessment of the pollution potential of applied fertilizers.

Economically optimizing the ability of a given soil or overburden material to supply those essential nutrients required for a given crop within the limits of the other factors is the goal of any fertilizing recommendation, and it is the purpose of this section to evaluate the effects of this goal on the groundwater quality of a coal strip mine.

IDENTIFY POTENTIAL POLLUTANTS

Fertilizer sources most likely to affect the quality of water within reclaimed areas include the major mineral nutrients nitrogen and phosphorus

and certain micronutrients, if applied in relatively large amounts. Ammonium nitrate is entirely soluble in water when used as a fertilizer. Nitrate-nitrogen (NO_3-N) is immediately available to plants, as this is the form that plants primarily absorb, although some plants have ability to absorb small amounts of ammonia-nitrogen (NH_3-N) by direct cation exchange.

Because ammonia and nitrate-nitrogen have the ability to move up and down in the soil solution, both should be included in the monitoring effort. The cationic nature of NH_3-N permits its adsorption and retention by soil colloidal material if the cation exchange capacity of the soil is sufficiently high; otherwise, it will be removed in percolating water. Nitrate is highly subject to leaching, as it is completely mobile in soils. Hence, its inclusion in the monitoring effort is highly justified.

Because the phosphate ion is almost immobile in soil, phosphorus moves very slowly from the point of placement. Also, the activity of phosphorus is lower in alkaline or calcareous soils due to the high Ca^{+2} activity, the large amount of finely divided calcium carbonate, and the large amount of calcium-saturated clay, all of which contribute to the precipitation of phosphate on solid phase calcium carbonate. Therefore, phosphorus is a doubtful source of groundwater contamination and should not be included in the monitoring effort.

Monitoring Needs

Due to lack of existing data, nutrients being applied to reclaimed areas must be delineated.

Alternative Monitoring Approaches

Pollutant-specific information on monitoring activities by the coal company relating to fertilizer application on reclaimed areas could be collected. For example, any existing water quality data may be requested together with information on fertilizer application. Alternatively, the areas receiving fertilizer application could be clearly delineated, along with the nature of the application and its rate.

Water samples for characterizing pollutants associated with fertilizer application could be obtained from surface waters adjacent to reclaimed areas. Samples could be collected before and after fertilizer has been applied, with increases in the concentration of particular constituents being noted.

These alternative methods are possible for analyzing surface water samples. First, all samples may be submitted for complete analyses, including: the major inorganics (nitrate-nitrogen, ammonia-nitrogen, calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate, phosphate, silica, total nitrogen, pH, and electrical conductivity) and trace constituents (iron, manganese, zinc, copper, cadmium, chromium, arsenic, molybdenum, vanadium, and selenium).

A second technique is to completely analyze the first few water samples collected during the program. Subsequently, those constituents known to be applied as fertilizer would continue to be analyzed, whereas those not applied as fertilizer could be excluded from further analyses.

A third method is to analyze only for those constituents known to be applied as fertilizers, and exclude any fertilizer constituents found to be present in low concentrations from further analyses.

Selecting a sampling frequency to characterize the water-borne pollutants in a source, such as applied fertilizer, is generally dependent upon the concentration and rate at which the fertilizer is applied. One method is to sample frequently (e.g., every few days or weekly) until time trends in the quality of the source are characterized. Subsequently, samples would be obtained by periodic sampling (e.g., weekly or monthly). An increase in sampling frequency may be warranted by unusual circumstances. For example, a spill of fertilizer on the watershed area draining into surface water could justify an increase in sampling frequency.

Preliminary Recommendations

All areas receiving fertilizer application should be delineated, along with the nature of the application and its rate. Surface water in the area should be sampled before and after fertilizer application to characterize the present water quality and quantity trends. Initial water samples would be analyzed completely, with later samples analyzed only for those constituents present in the fertilizer applied to the reclaimed areas.

Costs include: labor costs for data collection and sampling, and operational costs for analyses and miscellaneous sampling equipment. These costs are given in Table A-2.

DEFINE GROUNDWATER USAGE

Irrigation of reclaimed spoils is not planned at any of the mines at present; however, it may be a possibility in the future.

Monitoring Needs

Primary data required by monitoring pertain to determining whether reclaimed areas will be irrigated and, if so, what the irrigation requirements will be in terms of water quality and quantity.

Alternative Monitoring Approaches

Anticipated use of groundwater for irrigation of reclaimed land could be assessed through discussions with mine personnel. If irrigation is being used, the quantity of water could be monitored with irrigation metering devices installed in the supply lines. The volume of water needed for irrigation could also be estimated by assuming a consumptive use of 1 to 4 acre-feet of water per acre being revegetated.

Preliminary Recommendations

The recommended preliminary approach is to determine whether spoils are to be irrigated. No further monitoring would be planned until irrigation is decided upon. The only cost for this approach would be labor for discussions with mine personnel.

DEFINE HYDROGEOLOGIC SITUATION

Studies to evaluate the hydrogeology of a pollutant source area require determining: aquifer locations, depths, and areal extent; transmissivities of aquifers; areal distribution to potentiometric surfaces; depths to groundwater; areas and distribution of natural groundwater recharge; areas and magnitudes of natural groundwater discharge; and directions and velocities of groundwater flow (Todd et al., 1976). These items relate to saturated groundwater flow (i.e., in the zone of saturation). Data of the hydrogeologic properties of the vadose zone are also important in estimating pollutant mobility. Such properties include determining infiltration characteristics, the presence of potential perching layers, water content changes of sediments during deep percolation, and flow rates of water.

Characterization of the above items is of particular importance for the area encompasssing a specific source. That is, the hydrogeology should be clearly understood in a source-specific sense.

Monitoring Needs

The following data gaps exist relative to the areas encompassing fertilizer applications: vadose zone properties (geology, lithology, etc.), and saturated zone properties, including locations of aquifers and associated geology and hydraulic head distributions, transmissivities (including anisotropic T) and storage coefficients of aquifers, and direction and velocities of groundwater flow.

Alternative Monitoring Approaches

An initial procedure could be to conjecture as to the nature of the reclaimed soil and overburden materials utilizing mine plans. This could be followed up by field reconnaissance.

Alternatively, field tests could be commenced to determine the physical properties of the reclaimed area spoil. These tests are an integral part of the monitoring approach in that the hydrogeologic situation will be highly modified.

Physical characteristics (including texture, consistency, depth, structure, colloidal content, and saturation percentage) of spoil and topsoil used for dressing could be determined.

Once the spoil has been physically characterized, tensiometers could be installed into the soil and spoil material composing the modified hydrogeology. Individual units could terminate at successive depths, e.g., 3 inches,

6 inches, 12 inches, 24 inches, 36 inches, and 60 inches below the reclaimed surface. Tensiometer data could be used with water content data, obtained by sampling by neutron logging, to estimate the hydraulic conductivity and flux.

Alternatively, access wells could be installed to the depth of the water table and logged routinely with a neutron moisture probe for evidence of seepage to the water table.

Dry drilling methods could be employed to obtain soil and spoil samples. A hollow stem auger is capable of providing the most useful background water quality data in the vadose zone. However, unconsolidated materials may present some problems.

Analyses of collected soil samples could include the measurement of pH, SAR, calcium, magnesium, chloride, alkalinity, CEC, chemical oxygen demand, and analysis for the ammonium and nitrate ions. These analyses would be completed prior to any fertilizer application. These analyses would serve to characterize the soil and spoils of the area under consideration prior to fertilizer application, with subsequent analyses restricted to the measurement of pH, ammonium, and nitrate.

If a saturated zone is detected in existing wells in the reclaimed area, or while obtaining solid samples, sampling holes could be completed as wells and pump tests conducted.

Preliminary Recommendations

The following approach is recommended initially for hydrogeological studies:

- Collect available data on the modified hydrogeology of reclaimed areas
- Conjecture as to the nature of soil and overburden materials by field reconnaissance.

Costs for this step include labor for reconnaissance field study and field transportation. Costs for these items are given in Table A-2. Data compilation, review, and testing are covered in defining the hydrogeologic situation for regraded mine spoils described in Section 1.

STUDY EXISTING GROUNDWATER QUALITY

The general purpose of determining groundwater quality in the vicinity of a source, such as applied fertilizers, is to characterize the impact of pollutant movement on the indigenous quality. Two types of information are required: background quality and current quality. Activities during this step will overlap related steps involving characterizing the hydrogeologic situation and determining the attenuation of pollutants in the zone of saturation.

Monitoring Needs

Data deficiencies exist in the following: current areal distribution of groundwater quality in reclaimed areas receiving fertilizer and time trends in the quality of groundwater beneath reclaimed areas.

Alternative Monitoring Approaches

If any wells exist in reclaimed areas, information, including depth of well, location of perforations and water quality data, could be collected.

A water sampling program could be initiated to characterize the current groundwater quality in the vicinity of the source. Methods include: sampling from existing monitor wells in the reclaimed area, installation of supplemental wells, and a combination of the two. Monitor wells required by the second method would only be constructed following assessment of a serious pollution threat to the existing groundwater quality.

Water samples could be obtained by a variety of alternative techniques: submersible pump, hand bailing, air-lift pump, etc. The submersible pump permits redevelopment of the well and rapid sample collection. The latter feature is desirable in light of the recommendation that at least five casing volumes be removed prior to sample collection (Mooji and Rovers, 1976). Hand bailing is a viable method in small-diameter casing. Air-lift pumps introduce air into the sample, causing changes in unstable constituents, such as pH, DO, and alkalinity.

Three possible alternatives for water sample analyses are as follows: Samples could be completely analyzed for constituents listed above (Identify Potential Pollutants) in each category, major inorganics, and trace constituents. Alternatively, the first few water samples could be examined completely. Once the principal constituents are identified (primarily those occurring in greater-than-permissible levels), subsequent analyses would be for these constituents only. Note that this approach would be used only for those inorganics that are not applied as fertilizer. The ammonium-nitrogen and nitrate-nitrogen concentrations would be determined for each sample.

Primary Recommendations

The preliminary monitoring approach would be to collect all available water quality data from wells in the reclaimed area. Groundwater samples would then be collected from existing wells and supplemental wells constructed to evaluate specific pollutant sources. A submersible pump would be used for sample collection, and each well would be pumped for a sufficient period of time to remove five casing volumes before sampling.

Initial water samples would be analyzed completely; while subsquent analyses would be only for those constituents found to occur in greater-than-permissible concentrations. Ammonium-nitrogen and nitrate-nitrogen concentrations would be determined for each sample.

Samples would be taken on a weekly basis until time trends in quality are established. Thereafter, samples would be obtained on a bimonthly basis. Unusual events may necessitate a greater sampling frequency.

Costs for this step include: labor costs for collecting and interpreting existing water quality data and taking samples, operational costs for sample analyses, and capital costs for submersible pumps, etc. These data have been compiled for defining existing groundwater quality in the preliminary monitoring design for regraded spoils (Table A-1) and will not accrue additional costs here.

EVALUATE INFILTRATION POTENTIAL

The purpose of determining the infiltration potential of a source is to quantify the volume of water and associated pollutants moving to the underlying saturated zone.

The priority ranking report (Everett, 1979) indicates that the natural material used for surface dressing is expected to have a higher infiltration than the spoil material, but lower, after settlement, than the structured natural soils.

Monitoring Needs

The primary information needed by monitoring is the quantity of water which infiltrates the fertilized spoil surface.

Alternative Monitoring Approaches

Infiltration capacity could be determined by laboratory tests of spoil permeability, ring infiltrometers, or sprinkler-type infiltrometers. These are discussed in the monitoring design for infiltration capacity of spoils in Section 1.

Preliminary Recommendations

Infiltration capacity would be determined using a simple ring infiltrometer. Sites would be selected on the basis of information collected during identification of potential pollutants for spoils.

Costs for this step include: labor costs for infiltration measurements and data collection and capital costs for ring infiltrometers. These costs would be attributed to the preliminary monitoring design for regraded mine spoils monitoring step, Evaluate Infiltration Potential (Table A-1).

EVALUATE MOBILITY OF POLLUTANTS IN THE VADOSE ZONE

The general purpose of this step is to estimate or measure the movement of pollutants in the vadose zone underlying a source or sources. Pollutants associated with fertilizers will be specified upon implementation of the step, Identify Potential Pollutants. Similarly, the potential for pollutants

to move into the vadose zone from the point of application will be determined during the above step (Evaluate Infiltration Potential).

As previously mentioned, ammonium nitrate is completely soluble if sufficient moisture exists to dissolve it. Once dissolved, the two types of nitrogen salt which compose this fertilizer have the ability to move up and down in the soil solution.

Tisdale and Nelson (1975) discussed the retention of nitrate-nitrogen in soil.

Once ammonia is nitrified, it is subject to leaching. Nitrate-nitrogen is completely mobile in soils and within limits moves largely with the soil water. Under conditions of excessive rain, it is leached out of the upper horizons of the soil. During extremely dry weather and when capillary movement of water is possible, there is an upward movement with the upward movement of the water. Under such conditions, nitrates will accumulate in the upper horizons of the soil or even on the soil surface.

Figure 1 illustrates the pattern of nitrate distribution in some columns of soils which differed in their particle-size distribution. The percentage of large pore space and the amount of coarse sand decreased from sample A to sample H, although the total pore space remained relatively constant (Tisdale and Nelson, 1975).

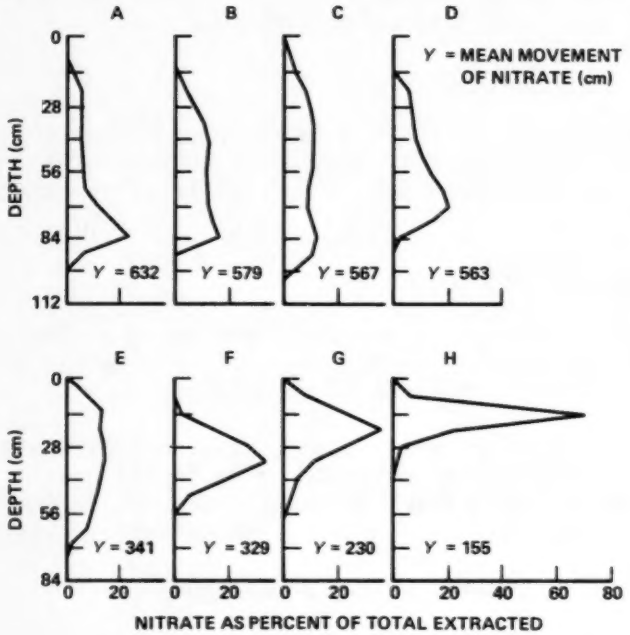

Figure 1. Distribution of nitrates through columns of coarse-textured soils after adding 3.29 cm of water (after Tisdale and Nelson, 1975).

TABLE 1. PROCESSES WHICH MAY CONTROL AMOUNTS OF CERTAIN CONSTITUENTS IN SUBSURFACE WATERS CONTAMINATED BY WASTE DISPOSAL[a]

	Physical				Geochemical					Biochemical	
Constituent	Dilution	Disperson	Filtration	Complexation	Ionic strength	Acid-base	Oxidation-reduction	Precipitation-soln.	Adsorption-desorption	Decay, respiration	Cell synthesis
Cl^-, Br^-	x	x									
NO_3^-	x	x					x			x	x
SO_4^{2-}	x	x		(x)	(x)	(x)	x		(x)	(x)	
HCO_3^-	x	x		(x)	(x)	x		x		x	
PO_4^{3-}	x	x		x	x	x		x	x	x	x
Na^+	x	x			(x)				x		
K^+	x	x			(x)				x		
NH_4^+	x	x		x	(x)	x	x		x	x	x
Ca^{2+}	x	x		(x)	x			(x)	x		
Mg^{2+}	x	x		(x)	x			(x)	x		
Fe^{2+}	x	x		x	x	x	x	x	x		
Mn^{2+}	x	x		x	x	x	x	x	x		
Fe^{3+} and MN^{4+} oxyhydroxides	x	x	x			x	x	x			
Organic solutes	x	x		x	(x)	x	x	(x)	(x)	x	x
Microorganisms	x	x	x				x			x	x

NOTE: ( ) denote minor controls.

[a] from Langmuir, 1972.

Monitoring Needs

Data gaps exist in knowledge of the factors tending to attenuate pollutants within the vadose zone (i.e., dilution, filtration, sorption, chemical precipitation, buffering, oxidation reduction, volatilization, and biological degradation and assimilation), and in field data on transformations in waterborne pollutants during flow in the vadose zone.

Alternative Monitoring Approaches

The potential attenuation of pollutants in the vadose zone may be depicted by constructing a matrix (table) comprising attenuating factors (rows) versus specific pollutants (columns). An example (Table 1) of such a matrix has been prepared by Langmuir (1972). Each location in the matrix would specify the relative potential of a factor (e.g., sorption) to attenuate a

specific pollutannt (NH_4^+). Each position in the table may be filled in by subjective evaluation or on the basis of actual measurement. Subjective evaluation would involve examining available data and estimating the effect on the mobility of a specific pollutant. Alternatively, actual values from attenuating factors may be obtained from field measurements. For example, spoil samples obtained in a previous step may provide analytical data on pollutant mobility.

A second method is to use instruments installed during a previous monitoring step to determine the water (and pollutant) movement in the vadose zone. These instruments included access wells (neutron moisture logging) and tensiometers.

Field activities could be initiated to monitor the actual movement of pollutants in the vadose zone. Alternative methods include: collecting drill or auger samples for laboratory analysis and installing suction-cup lysimeters.

Collection of samples of vadose zone sediments would entail using hand or power augers, or core samplers. Depending on physical composition of the spoil underlying the fertilized areas, hand-augered samples could be obtained to a depth of about 10 feet. If deeper samples were required, power equipment would be needed.

Suction-cup lysimeters could be installed in selected portions of the vadose zone and within the fertilized areas at depths corresponding to tensiometer locations. Collection bottles and the vacuum supply would be located in buried shelters, and vacuum and discharge lines from the suction-cup lysimeter and tensiometer units would be positioned within conduit. During sampling, vacuum would be applied to the samplers equivalent to water content pressure in tensiometers. Note, suction-cup lysimeters become inoperable at soil water pressures less than -0.8 atmosphere.

Water samples collected from suction-cup lysimeters could be analyzed completely or partially. Ideally, a complete analysis includes the major inorganics and trace constituents listed under Identify Potential Pollutants. Upon examination of the results of complete analysis, it may be opted to analyze subsequent samples only for those constituents found present in greater-than-permissible concentrations, and for those constituents present in applied fertilizer.

Solid samples could be used to obtain saturated extracts via techniques in methods of soil analysis (Black, 1965).

Sampling frequency for suction-cup lysimeters depends on the water pressure within the surrounding porous matrix. Thus, if the system is very dry, water will enter the samplers at a very slow rate. A week or more may be required before a sufficient sample is available for analysis. In the extreme case, the samplers may become inoperable (i.e., when water pressure is less than -0.8 atmosphere). In this case, samples may become available only once or twice a year. Sampling frequency cannot be explicitly determined until

field units are installed and operating. For a wet system, it may be desirable to collect samples on a frequent (e.g., weekly) basis until quality trends are established. Later, samples could be obtained once a month.

Solid samples could be collected at a variety of frequencies, e.g., monthly, bimonthly, semiannually, or annually.

Preliminary Recommendations

The preliminary monitoring program would include constructing a matrix of attenuating factors versus specific pollutants using available data when possible, supplemented with intuition. Water movement in the vadose zone underlying fertilized areas would be determined using facilities installed during the step, Define Hydrogeologic Situation. A few suction-cup lysimeters would be installed at depths corresponding to tensiometer locations, with samples analyzed as discussed above. Samples would be collected whenever possible during very dry conditions. For wet conditions, samples would be taken more frequently until quality trends are established. Thereafter, samples would be analyzed once a month.

Costs for this step include labor costs for constructing an attenuation factor versus pollutant matrix and interpreting results, installing suction-cup lysimeters, and collecting samples; operational costs for analyses; and capital costs for the suction-cup lysimeters. These costs are given in Table A-2.

EVALUATE ATTENUATION OF POLLUTANTS IN THE SATURATED ZONE

The general purpose of this step is to estimate or measure the attenuation of source pollutants during flow in the zone of saturation. Obviously, the pollutants of concern will be those which have not been completely attenuated during flow through the vadose zone. As pointed out by Todd et al. (1976), the principal processes involved in attenuating pollutants in the zone of saturation include physical-chemical reactions or dilution. For pollutants in a source such as fertilizer, physical-chemical processes are sorption, precipitation, volatilization, oxidation-reduction reactions, etc. Dilution is effected by hydrodynamic dispersion resulting from such effects as convection diffusion, and flow tortuosity.

Monitoring Needs

Information gaps currently exist in predicting the effect of physical-chemical reactions and dilution on pollutant mobility within aquifers underlying fertilized aeas.

Alternative Monitoring Approaches

The relative effect of various physical-chemical mechanisms for attenuating pollutants within the saturated zone could be estimated by constructing a matrix, similar to that for the vadose zone. That is, a table would be prepared consisting of attenuating mechanisms (rows) versus pollutants (columns). Attenuating mechanisms would consist of the following: physical-chemical

factors, i.e., sorption, precipitation, volatilization, oxidation-reduction (Eh), decay, and dilution. When completed, the table would show in a mixed qualitative-quantitative sense the pollutants which should be monitored.

Completion of the matrix for the physical-chemical items requires specific information on exchange capacity of aquifer materials, on the Eh and pH of groundwater, as well as on the specific pollutants entering the zone of saturation. Many of the physical-chemical parameters could be quantified from analysis of drill cuttings obtained during well construction and from field analysis of Eh and pH. Identification of pollutants must await results of mobility studies in the vadose zone.

Groundwater samples could be obtained for analysis and ensuing data examined to characterize pollutant attenuation. Existing wells and wells installed during previous steps could be used in such a program. In actuality, a special sampling program would not be required because samples would be available from these steps.

Preliminary Recommendations

The recommended preliminary approach would include all of the methods discussed above. Costs for this step include only labor costs for construction of the attenuation factor versus pollutant matrix. This cost is given in Table A-2.

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APPENDIX A

SUMMARY OF PRELIMINARY MONITORING DESIGNS

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TABLE A-1. SUMMARY OF PRELIMINARY RECOMMENDED MONITORING APPROACHES FOR REGRADED MINE SPOILS

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Identify potential pollutants (spoils)	1. Characterize type, concentration, and distribution of potential pollutants in spoils	Nonsampling method 1. Consult mining records on amount and location of spoil placement during backfill operations 2. Determine materials which received special handling and emplacement Sampling method 1. Compile monthly maps of location and elevation of spoils in reclaimed areas 2. Maintain monthly photographic record of the face of the regraded spoils 3. Calculate or estimate gross weight or volume of backfilled materials 4. Conduct composite or priority sampling program described in text 5. Analyze spoil samples for pH, EC, TDS, TOC, sulfate, nitrate, total nitrogen, boron, fluoride, selected trace elements, and radiologic activity and species	1. Compile available mine records on backfill operations and determine which materials received special handling 2. Map and photograph backfill areas, update information monthly 3. Use priority sampling method to characterize spoils 4. Analyze spoil samples for pH, EC, TDS, TOC, sulfate, nitrate, total nitrogen, boron, fluoride, selected trace elements, and radiologic activity and species	1. Labor a. Compile and review mine reclamation data (3 days): $180 b. Sample handling preparation, quality control, etc: $10/sample c. Mapping and photography (1 week) geologist and assistant: $500; monthly update (2 days): $200 2. Operation a. Chemical analysis: $100/sample b. Air freight, refrigeration, packing, etc: $25/set, 3 to 8 samples c. Field transportation: $0.17/mile 3. Capital a. Sample containers, labels, field books, chemicals, etc: $2.50/sample b. Photographic supplies: $2/day c. Power hole auger: $300
Define groundwater usage	1. Determine if irrigation is planned for backfilled materials	Nonsampling method 1. Interview mine personnel to determine if regraded spoils will be irrigated 2. Calculate consumptive water use for revegetation Sampling method 1. Install flow meters in irrigation system delivery lines to determine water usage	1. Determine if irrigation is proposed for revegetation	1. Labor a. Interview mine personnel to determine if irrigation is proposed for revegetation (1 day): $40 2. Operation None 3. Capital None

(continued)

TABLE A-1 (continued)

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Define hydrogeologic situation	1. Define undisturbed groundwater system 2. Determine rate of invasion of groundwater into regraded spoils	Nonsampling method 1. Compile existing hydrologic data from wells within and adjacent to the mine area 2. Compile geologic data from published material, mine reports, and oil or water well logs Sampling method 1. Initiate water level survey 2. Conduct aquifer tests of selected wells to determine transmissivity and storage coefficient	1. Compile hydrogeologic data in vicinity of reclamation area 2. Conduct aquifer test and compile water level measurements, as necessary (see monitoring step, Evaluate Attenuation of Pollutants in the Saturated Zone for aquifer test costs)	1. Labor a. Compile and review existing hydrogeologic data (2 weeks): $600 2. Operation a. See monitoring step, Evaluate Attenuation of Pollutants in the Saturated Zone 3. Capital a. See monitoring step, Evaluate Attenuation of Pollutants in the Saturated Zone
Study existing groundwater quality	1. Characterize site-specific groundwater quality in terms of physical and chemical constituents	Nonsampling method 1. Compile water quality data from mine operators, U.S. Geological Survey, State agencies, private consultants, etc. Sampling method 1. Initiate water sampling program to characterize major inorganics, trace constituents, organics, and microoroganisms 2. Develop field program to periodically check water quality for pH, EC, DO, nitrate, and chloride	1. Evaluate water quality from available records 2. Initiate water sampling program if additional or site-specific data are required 3. Conduct periodic field checks with laboratory samples taken when marked changes occur in parameters monitored	1. Labor a. Compile and review water quality data (1 week): $300 b. Sample handling, laboratory preparation, quality control, handling, etc: $5/sample c. Sample-equipment installation: $40/day d. Field check water quality: $2.50/sample 2. Operation a. Chemical analysis: $200/sample b. Field transportation: $0.17/mile c. Air freight, packing, refrigeration, etc., for water quality samples: $10/set, 1 to 3 samples 3. Capital a. Field kit, bailer, and storage chest: $750 b. Bottles, labels, chemicals: $2.50/sample

(continued)

TABLE A-1 (continued)

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Evaluate infiltration potential	1. Characterize infiltration potential of regraded spoils	Sampling method 1. Conduct laboratory permeability test of spoils 2. Use ring infiltrometers to measure infiltration 3. Utilize sprinkler-type infiltrometers	1. Use ring infiltrometer to assess infiltration into regraded spoils	1. Labor a. Installation of infiltrometer: $10 b. Conduct infiltration test: $9/test 2. Operation a. Field transportation: $0.17/mile 3. Capital a. Double-ring infiltrometer: $150
Evaluate mobility of pollutants in the vadose zone	1. Characterize quantity and quality of water moving through the vadose zone	Nonsampling method 1. Use maps and survey results developed during monitoring step, Identify Potential Pollutants, discussed above, to estimate expected water quality and quantity Sampling method 1. Determine unsaturated, unsteady flow in terms of moisture content and pressure changes with time and depth 2. Use electrical resistivity, neutron scattering, or gravimetric methods to measure soil moisture content 3. Use pressure plates, psychrometers, or tensiometers to measure changes in spoil pore pressure 4. Groundwater quality will be monitored during monitoring step, Study Existing Groundwater Quality	1. Delineate sampling sites using maps and surveys developed above 2. Conduct soil moisture study using neutron probes 3. Evaluate soil pressure changes using tensiometers	1. Labor a. 100-ft neutron probe access hole: $250/site b. Neutron logging survey: $50/site c. Tensiometer installation: $30/site 2. Operation a. Field transportation: $0.17/mile 3. Capital a. Neutron logger and generator: $15,000 b. Hardware and supplies to complete neutron access well: $5/ft (including seamless steel pipe at $3.12/ft) c. Tensiometers: $20 each

(continued)

TABLE A-1 (continued)

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Evaluate attenuation of pollutants in the saturated zone	1. Determine aquifer characteristics of saturated spoils 2. Characterize physical and chemical constituents of groundwater in spoils	Nonsampling method 1. Review site-specific hydrogeologic data compiled in earlier monitoring steps (Define Hydrogeologic Situation) Sampling method 1. Conduct aquifer pump test in and adjacent to regraded spoils 2. Collect water level measurements in and adjacent to regraded spoils	1. Review site-specific hydrogeologic data 2. Conduct aquifer test in regraded spoils 3. Collect water quality samples from well developed in spoils	1. Labor a. Review hydrogeological data (completed for earlier monitoring steps) b. Drilling labor and supervision for monitoring well, with equipment: $93/hour c. Sample handling, quality control, laboratory preparation: $5/sample d. Pumping tests (3 persons): $140/day 2. Operation a. Chemical analysis: $200/sample b. Packing and air freight for water quality samples: $25/set, 4 to 8 samples c. Field transportation: $0.17/mile d. Pump test (equipment rental and operation): $3,000/test) e. Field check water quality: $2.50/sample 3. Capital a. Field kit and storage chest: $730 b. Hardware and supplies for monitor well completion: $15/ft c. Bottles, labels, field notebooks, chemicals, etc: $2.50/sample d. Water level sounder: $200

TABLE A-2. SUMMARY OF PRELIMINARY MONITORING DESIGN FOR RECLAMATION AIDS

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Identify potential pollutants	1. Delineate nutrients being supplied to reclaimed areas as fertilizer	Nonsampling method 1. Determine fertilizer application on reclaimed area through mine company records Sampling method 1. Sample surface waters adjacent to reclaimed areas for fertilizer-related pollutants 2. Analyze water quality samples for major inorganics, trace constituents, total nitrogen, pH, EC	1. Define areas receiving fertilizers 2. Sample surface waters before and after fertilizer application 3. Analyze first few samples completely and later samples for fertilizer components only	1. Labor a. Review mine reclamation plans (2 days): $80 b. Sample handling, quality control, laboratory preparations: $5/sample 2. Operation a. Field transportation: $0.17/mile b. Chemical analysis: $200/sample c. Packing, air freight: $10/set, 1 to 3 samples 3. Capital a. Bottles, lables, field chemicals: $2.50/sample
Define groundwater usage	1. Determine irrigation requirements	Nonsampling method 1. Determine if groundwater will be utilized for irrigation during reclamation through discussions with mine personnel	1. No monitoring will be planned until an irrigation program is established	1. Labor None 2. Operation None 3. Capital None
Define hydrogeologic situation	1. Characterize relationship between areas of fertilizer application and the site-specific hydrogeology	Nonsampling method 1. Utilize available mine records compiled to characterize mine spoils Sampling method 1. Field test physical characteristics of regraded spoils 2. Use a combination of tensiometer and neutron logging data to determine hydraulic conductivity and flux in spoils	1. Collect available data on modified hydrogeology of reclaimed areas 2. Infer nature of near-surface spoils from field reconnaissance	1. Labor a. Compile and review hydrogeologic data (completed in Monitoring Design for Regraded Mine Spoils) b. Reconnaissance field study (3 days): $120 2. Operation a. Field transportation: $0.17/mile

(continued)

TABLE A-2 (continued)

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Define hydrogeologic situation (continued)		3. Obtain soil and spoil samples using dry drilling methods or augering 4. Conduct pump test on wells completed in saturated zone		3. Capital None
Study existing groundwater quality	1. Define quality and time trends of groundwater within and beneath reclaimed areas	Nonsampling method 1. Collect data on existing well in reclaimed area Sampling method 1. Sample existing or supplemental wells for water quality	1. Evaluate water quality from available records 2. Sample existing or supplemental wells using recommended sampling technique 3. Analyze initial samples completely with subsequent tests for species concentrated above site-specific background levels	Labor, operation, and capital costs for this monitoring step would be the same as for Study Existing Groundwater Quality for Regraded Mine Spoils (Table A-1) and would be attributed to that monitoring step.
Evaluate infiltration potential	1. Define quantity of water which infiltrates the fertilized spoil surface	Sampling method 1. Infiltration can be determined by ring, sprinkler-type infiltrometers, or laboratory permeability tests	1. Use ring infiltrometers to measure infiltration into regraded spoils	Labor, operation, and capital costs are assigned to monitoring step, Evaluate Infiltration Potential for Regraded Spoils
Evaluate mobility of pollutants in the vadose zone	1. Define pollutant attenuation factors during flow through vadose zone	Nonsampling method 1. Develop matrix table of pollutants (columns) versus attenuating factors (rows) for subjective evaluation of attenuation of pollutants in the vadose zone Sampling method 1. Install neutron moisture logging equipment and tensiometer to determine fluid movement in the vadose zone 2. Collect (drill or auger) soil, spoil samples from the vadose zone 3. Install suction-cup lysimeters to sample soil moisture	1. Construct pollutant attenuation matrix table 2. Utilize data completed in earlier monitoring steps (Define Hydrogeologic Situation and Evaluate Mobility of Pollutants in the Vadose Zone, Table A-1) to evaluate attenuation 3. Install a limited number of suction-cup lysimeters and tensiometers to evaluate soil moisture	1. Labor a. Construct pollutant attenuation matrix (3 weeks): $900 b. Field installation of suction-cup lysimeters: $30/site c. Sample handling, quality control, laboratory preparation: $51/sample d. Field installation of tensiometers: $30/site 2. Operation a. Chemical analysis of soil/spoil moisture samples: $200/sample b. Field transportation: $0.17/mile

(continued)

TABLE A-2 (continued)

TEMPO monitoring steps	Monitoring needs	Alternative monitoring approaches	Preliminary recommendations	Monitoring costs
Evaluate mobility of pollutants in the vadose zone (continued)				c. Packing, air freight for water quality samples: $10/set, 1 to 3 samples 3. Capital a. Bottles, labels, chemicals, etc: $2.50/sample b. Suction-cup lysimeters: $4 each c. Tensiometers: $20 each
Evaluate attenuation of pollutants in the saturated zone	1. Determine attenuation of source pollutants during flow in zone of saturation	Nonsampling method 1. Construct attenuation matrix for saturated zone similar to that for the vadose zone Sampling method 1. Use aquifer characteristics (disturbed and undisturbed) and water quality analysis collected in alternative monitering steps (Identify Potential Pollutants, Study Hydrogeologic Situation, Evaluate Mobility of Pollutants in the Vadose Zone and Evaluate Attenuation of Pollutants in the Saturated Zone, Table A-1) to evaluate pollutant attenuation in saturated zone	1. Construct attenuation matrix table for saturated zone 2. Evaluate attenuation of pollutants based on available and developed data	1. Labor a. Construct pollutant attenuation matrix (3 weeks): $900 2. Operation None 3. Capital None

APPENDIX B

METRIC CONVERSION TABLE*

Nonmetric units	Multiply by	Metric units
inch (in)	25.4	millimeters (mm)
	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
square feet (ft^2)	0.290×10^{-2}	square meters (m^2)
yards	91.44	centimeters (cm)
square yards	0.914	square meters (m^2)
miles	1.6093	kilometers (km)
square miles	3.599	square kilometers (km^2)
acres	4.047×10^3	square meters (m^2)
	4.047×10^{-1}	hectares (ha)
gallons	3.785×10^3	cubic centimeters (cm^3)
	3.785×10^{-3}	cubic meters (m^3)
cubic feet (ft^3)	3.785	liters (l)
barrels (oil)	1.590×10^2	liters (l)
acre/ft	1.108×10^7	liters (l)
gallons/square foot per minute	40.74	liters/square meter per minute
cubic feet/second	3.532×10^{-2}	liters/second
gallons/minute†	6.308×10^{-2}	liters/second
gallons/day	3.785	liters/day
million gallons/day	28.32	liters/second
	0.028	cubic meters/second
pounds	0.454	kilograms (kg)
	4.536×10^{-4}	tons (metric) (M.T.)
tons (short)	9.072×10^{-2}	kilograms (kg)
	0.907	tons (metric) (M.T.)
pounds/acre	1.122	kilograms/hectare (kg/ha)
parts per million (ppm)	1	milligrams per liter (mg/l)

* English units were used in this report becuase of their current usage and familiarity in industry and the hydrology-related sciences.

† 1 gpm = 1.6276 afa.